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Adaptive robust control for spatial hydraulic parallel industrial robot

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Abstract

This paper proposes an adaptive robust control for spatial hydraulic industrial robot, with a view of improving the performance of trajectory tracking under varying uncertainty. The mathematical models of mechanical system and electro-hydraulic driven system of spatial 6-DOF industrial robot are described, under Kane method and hydromechanics method. The backstepping design methodology is adopted to develop the nonlinear adaptive robust control scheme, which treats the modeling errors and coupling as bounded disturbances, and regards parameters without a priori knowledge as parametric disturbances. The dynamic tracking performances of the closed-loop system with the proposed control for the industrial robot are validated via simulation. The theoretical and simulation results demonstrate that the developed controller can exhibit good tracking performance

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1. Introduction

Hydraulic parallel industrial robots are often used in the fields of motion or mechanics environmental simulation, such as high precision space docking motion system, high fidelity flight simulator, vehicle simulator, ship simulator, and load test rigs, by virtue of their advantages of special loading capability,

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high stiffness, high accuracy, and high force-to-weight ratio and so on [1-2]. On the other hand, such parallel industrial robots have some disadvantages of strong dynamic coupling and high nonlinearity resulted from system complex dynamic characteristics, which may limit the potential development of hydraulic parallel robots. Therefore, high performance controller is necessary and significant for spatial hydraulically driven parallel industrial robot.

In system and control community, spatial parallel robot has attracted special attention to develop effective controller for a typical multi-input multi-output (MIMO) nonlinear system [3]-[4]. The control strategies for robots may be largely divided into two schemes, motion control [5]-[6], and model-based control [7]-[8]. Motion control can be readily implemented as a collection of multiple, independent single-input single-output control system using data on each actuator length only, but it does not always guarantee a high performance for any case. Model-based controllers are developed to improve control performance by taking dynamics characteristics of controlled member into account, such as robust control [9], and adaptive control [10]. The adaptive controllers are presented for industrial robots in [11], yet, the property of driven system is not considered. In [12], the electronically driven systems are considered in control design. Unlike electrically driven robots, hydraulic robots exhibit significant nonlinear actuator dynamics, which is more challenging.

The main contribution of this paper is to propose an adaptive robust controller (ARC) for spatial hydraulic parallel robot with high nonlinearities and uncertainty to get excellent tracking performance. The spatial industrial robot is described as multi-rigid bodies, for which the dynamics is described using Kane method, as well as hydraulic system obtained by applying hydrodynamics. With consideration of the dynamics of the nonlinear driven system and multi-body system, the adaptive robust control, based on backsteping methodology, is designed to improve control performance of hydraulic industrial robot. The system friction is compensated by a LuGre model updated with adaptive control, and the system uncertainties are rejected by a robust control law.

2. Hydraulic Robot Dynamics

The kinematics and dynamics of spatial parallel industrial robot have been investigated extensively [1-2]. Hence, the dynamic equation of mechanical system is briefly described for the parallel industrial robot. The dynamic model of hydraulic robot can be described as

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\bar{\boldsymbol{q}}} + \boldsymbol{C}(\boldsymbol{q},\dot{\bar{\boldsymbol{q}}})\dot{\bar{\boldsymbol{q}}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{J}_{l\bar{q}}{}^{T}(\boldsymbol{q})\boldsymbol{F}_L \tag{1}$$

$$q_{Li} = c_d \cdot w \cdot x_{vi}\sqrt{\frac{1}{\rho}(p_s - \mathrm{sign}(x_{vi})p_{Li})} \tag{2}$$

$$q_{Li} = A_1 \cdot \dot{l}_i + c_{tc}p_{Li} + c_{tic}p_s + \frac{(1+n^4)\cdot A_1 \cdot L}{2(1+n^2)(1+n^3)E}\dot{p}_{Li} \tag{3}$$

$$A_1 p_{Li} = F_{ai} + F_{fi} \tag{4}$$

where $\boldsymbol{M}(\cdot)$ is a 6×6 mass matrix, $\boldsymbol{C}(\cdot)$ is a 6×6 centrifugal terms, $\boldsymbol{G}(\cdot)$ is the gravity term, $\boldsymbol{J}_{l\bar{q}}(\cdot)$ is a 6x6 Jacobian matrix between generalized velocity of the moving platform and actuator velocity, $\boldsymbol{F}_L$ is a 6x1 actuator output force vector, $\dot{\bar{\boldsymbol{q}}}$ is the generalized velocity in inertial frame, $\boldsymbol{q}$ is generalized pose of the moving platform of hydraulic parallel industrial robot, q_{Li} is load flow, w is area gradient, x_{vi} is valve position, ρ is fluid density, p_s is supply pressure, A_1 is effective acting area of piston, c_{tc}, c_{tic} are the leakage coefficients, p_{Li} is load pressure, E is bulk modulus of fluid, c_d is flow coefficient, n is the ratio of area, $n = A_2/A_1$, F_{fi} is joint space friction.

3. Control Design

The kinematics and dynamics of spatial parallel industrial robot have been investigated extensively [1-2]. Hence, the dynamic equation of mechanical system is briefly described for the parallel industrial robot. The dynamic model of hydraulic robot can be described as

The natural frequency of servo-valve is often chosen to be much higher than power mechanism. Hence, the flow equation of servo-valve can be linearized by using Taylor expansion.

$$q_{Li} = k_q x_{vi\,i} - k_{ci} p_{Li} = k_{qv} V_i - k_c p_{Li} \qquad \text{i=1,2, …,6} \tag{5}$$

where k_q is flow charge of servo-valve, k_c is flow-pressure coefficient, V_i is control voltage command of valve. Combing (3) with (5), the command of voltage of hydraulic servo-valve is derived as

$$\boldsymbol{V} = k_q^{-1}[A_1 \cdot \dot{\boldsymbol{l}} + c_{tic}\boldsymbol{p}_s + (k_c + c_{tc})\boldsymbol{p}_L + \frac{(1+n^4)\cdot A_1 \cdot L}{2(1+n^2)(1+n^3)E} \cdot \dot{\boldsymbol{P}}_L] \tag{6}$$

Equation (6) can be rewritten as

$$\dot{\boldsymbol{F}}_L = \boldsymbol{f}(\boldsymbol{V},\boldsymbol{F}_L) + \boldsymbol{g}(\dot{\boldsymbol{l}}) = \frac{2(1+n^2)(1+n^3)E}{(1+n^4)L}\left[k_q\boldsymbol{V} - (k_c + c_{tc})\boldsymbol{F}_L\right] + \left[-\frac{2(1+n^2)(1+n^3)E}{(1+n^4)L}(A_1\dot{\boldsymbol{l}} + c_{tis}\boldsymbol{p}_s)\right] \tag{7}$$

With respect to a real hydraulically driven parallel industrial robot, the strong coupling always exited in the nonlinear system. Besides, it is difficult to know the full dynamic model exactly, such as high frequency dynamic model, hard to derive, and friction parameters, hard to identify due to the precision of pressure sensor in hydraulic system, and external disturbance of parallel industrial robot. The dynamic model of the real robot can be linearized and parameterized in joint space, described as

$$\boldsymbol{M}_l(\boldsymbol{l})\ddot{\boldsymbol{l}} + \boldsymbol{C}_l(\boldsymbol{l},\dot{\boldsymbol{l}})\dot{\boldsymbol{l}} + \boldsymbol{G}(\boldsymbol{l}) + \boldsymbol{F}_f = \boldsymbol{Y}_l(\boldsymbol{l},\dot{\boldsymbol{l}},\ddot{\boldsymbol{l}})\boldsymbol{\theta}_l + \boldsymbol{Y}_F(\dot{\boldsymbol{l}})\boldsymbol{\theta}_f = \boldsymbol{F}_L \tag{8}$$

where $\boldsymbol{Y}_l(\boldsymbol{l},\dot{\boldsymbol{l}},\ddot{\boldsymbol{l}}), \boldsymbol{Y}_F(\dot{\boldsymbol{l}})$ are repressor matrices, $\boldsymbol{\theta}_l, \boldsymbol{\theta}_F$ are unknown parameters, corresponding to mass/ inertia and friction parameters, respectively. We define the following terms by

$$\boldsymbol{e} = \boldsymbol{l}_d - \boldsymbol{l}\,,\ \dot{\boldsymbol{l}}_r = \dot{\boldsymbol{l}}_d + \boldsymbol{\Lambda}\boldsymbol{e}\,,\ \boldsymbol{s} = \dot{\boldsymbol{l}}_r - \dot{\boldsymbol{l}} = \dot{\boldsymbol{e}} + \boldsymbol{\Lambda}\boldsymbol{e}\,,\ \widetilde{\boldsymbol{F}} = \boldsymbol{F}_{Ld} - \boldsymbol{F}_L \tag{9}$$

where $\boldsymbol{\Lambda}$ is 6×6 positive definite diagonal matrix, $\boldsymbol{l}_d$, $\dot{\boldsymbol{l}}_d$ are desired displacement and velocity vector, respectively, $\boldsymbol{F}_{Ld}$ is desired actuator force vector. For the high nonlinear system (6) and (8), we could design a proper control law with excellent tracking performance but without divergence for the robot under uncertainties. The control command is solved by the control law which is developed as

$$\boldsymbol{f}(\boldsymbol{u},\boldsymbol{F}_L) = \dot{\boldsymbol{F}}_{Ld} - \boldsymbol{g}(\dot{\boldsymbol{l}}) + \boldsymbol{\Gamma}\boldsymbol{s} + \boldsymbol{K}_F\widetilde{\boldsymbol{F}} \tag{10}$$

where $\boldsymbol{\Gamma}, \boldsymbol{K}_F \in \Re^{6\times 6}$ are positive definite diagonal matrices.

$$\begin{aligned}\boldsymbol{F}_{Ld} &= \hat{\boldsymbol{M}}_l(\boldsymbol{l})(\ddot{\boldsymbol{l}}_r + \boldsymbol{K}_d\boldsymbol{s}) + \hat{\boldsymbol{C}}(\boldsymbol{l},\boldsymbol{l})\dot{\boldsymbol{l}}_r + \hat{\boldsymbol{G}}(\boldsymbol{l}) + \hat{\boldsymbol{F}}_f + \boldsymbol{K}_p\boldsymbol{e} + \boldsymbol{u}_{np} \\ &= \boldsymbol{Y}_l(\boldsymbol{l},\dot{\boldsymbol{l}},\dot{\boldsymbol{l}}_r,\ddot{\boldsymbol{l}}_r)\hat{\boldsymbol{\theta}}_l + \boldsymbol{Y}_F(\dot{\boldsymbol{l}})\hat{\boldsymbol{\theta}}_F + \hat{\boldsymbol{M}}_l(\boldsymbol{l})\boldsymbol{K}_d\boldsymbol{s} + \boldsymbol{K}_p\boldsymbol{e} + \boldsymbol{u}_{np}\end{aligned} \tag{11}$$

where $\boldsymbol{K}_d, \boldsymbol{K}_p \in \Re^{6\times 6}$ are positive definite diagonal matrices. With the adaptive law

$$\dot{\hat{\boldsymbol{\theta}}}_F = \boldsymbol{\kappa}_F\boldsymbol{\Gamma}_F\boldsymbol{Y}_F(\dot{\boldsymbol{l}})^T\boldsymbol{s} \tag{12}$$

and the robust law

$$\boldsymbol{u}_{np} = \begin{cases}\tau_0\dfrac{\boldsymbol{s}}{\|\boldsymbol{s}\|}, & \|\boldsymbol{s}\| \ge \varepsilon \\ \tau_0\dfrac{\boldsymbol{s}}{\varepsilon}, & \|\boldsymbol{s}\| \le \varepsilon\end{cases} \tag{13}$$

where $\hat{\boldsymbol{\theta}}_l \in \Re^6, \hat{\boldsymbol{\theta}}_F \in \Re^6$ are estimates of mass/inertia and friction parameters, respectively, updated using adaptive laws, $\hat{\boldsymbol{M}}_l(\cdot), \hat{\boldsymbol{C}}(\cdot), \hat{\boldsymbol{G}}(\cdot), \hat{\boldsymbol{F}}_f(\cdot)$ are estimated matrices corresponding to $\hat{\boldsymbol{\theta}}_l, \hat{\boldsymbol{\theta}}_F$, $\tau_0 > 0$ is the boundary of modeling errors, $\varepsilon > 0$ is a infinitesimal constant, kF is diagonal matrix.

Substituting (11) into (8), the error dynamics is formulated as

$$\boldsymbol{M}_l(\cdot)\dot{\boldsymbol{s}} + \boldsymbol{C}(\cdot)\boldsymbol{s} + \hat{\boldsymbol{M}}\boldsymbol{K}_d\boldsymbol{s} + \boldsymbol{K}_p\boldsymbol{e} = \tilde{\boldsymbol{F}} - \boldsymbol{Y}_q(\cdot)\tilde{\boldsymbol{\theta}}_l - \boldsymbol{Y}_F(\cdot)\tilde{\boldsymbol{\theta}}_F - (\boldsymbol{u}_{np} - \boldsymbol{\delta}) \tag{14}$$

where $\boldsymbol{\delta}(\cdot)$ is modeling error and disturbance.

By choosing the Lyapunov function V_1 to be

$$\boldsymbol{V}_1 = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{M}_l(\cdot)\boldsymbol{s} + \frac{1}{2}\tilde{\boldsymbol{\theta}}_F{}^T\boldsymbol{\Gamma}_F{}^{-1}\tilde{\boldsymbol{\theta}}_F + \frac{1}{2}\boldsymbol{e}^T\boldsymbol{K}_p\boldsymbol{e} + \frac{1}{2}\tilde{\boldsymbol{F}}^T\boldsymbol{\Gamma}^{-1}\tilde{\boldsymbol{F}} \tag{15}$$

According to dynamic properties of parallel industrial robot, the stability of the presented control law can be easily proved.

4. Results and Discussion

To show the performance of the proposed controller, numerical simulation is executed on a spatial 6-DOF hydraulic industrial robot. The solver, forth- and fifth-order Runge-Kutta method, is utilized to the control system, and the sampling time is set to 1ms.

The dynamic model of the hydraulic industrial parallel robot is established by using SimMechanics, a physical modeling approach according to physical relationships. It is assume that the dynamic model built by SimMechanics can be treated as actual plant of the hydraulic robot, in which all parameters are known. With respect to controller, the industrial robot is unknown in practice. It is assumed that friction parameters are 60% of their true value as the initial guesses, the uncertainty in mass and inertia is 10% of its real valve, and velocity feedback is available. With the developed controller, the motions: surge, yaw, heave, and circular motions are applied to the hydraulic industrial robot separately. The responses to the motions are illustrated in Fig.1

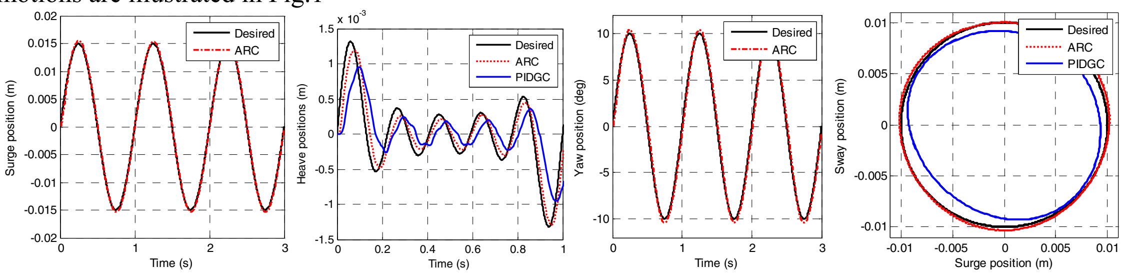

Fig. 1. Responses to the desired trajectories

In Fig.1, a well-tuned PID control with gravity compensation (PIDGC) is used to comparison, the developed adaptive robust controller shows remarkable tracking performances in all 6 DOF directions superior to PIDGC control scheme. For both single and combined motions, the ARC control scheme can repeat the desired sinusoidal, random, and circular trajectories with high tracking precision which is better than PIDGC control from the viewpoint of dynamic tracking performance.

5. Conclusions

This paper presented an adaptive robust control for spatial hydraulically driven industrial robot with uncertainties. The nonlinear dynamics with varied friction of the industrial robot is described by using

Kane method and hydrodynamics principle. A backstepping methodology is adopted to develop the nonlinear adaptive robust control law. The adaptive update law is adopted to deal with the parametric uncertainties of friction parameters, and the robust compensation law is employed to cope with the uncertainties of modeling errors and disturbances. The realization of the developed control law is available under the data feedback of actuator position, velocity, and pressure. With properties of robot dynamics, the closed-loop stability with the proposed controller is proved by using Lyapunov analysis. The trajectory tracking performance of the robot with the presented controller is evaluated through applying sinusoidal signals and circular signals. The results shown that the adaptive robust controller can exhibits excellent trajectory tracking performance for any inputs even without a prior knowledge. On the other hand, the proposed adaptive robust controller has some disadvantages, optimal tuning of parameters is difficult since many control parameters exist, and more information is required, such as velocity, load force of the hydraulic industrial robot, which should be solved to make it available in actual high real time control system as a good alternative.

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